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THORON PROGENY TO RADON PROGENY RELATIONSHIPS AT DENISON MINES LIMITED

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ABSTRACT

Radon-222 and ^{220}Rn progeny are found in some Canadian underground uranium (U) mines. Because both contribute to the worker's total radiation exposure, their experimental determinations are important. The relationship between ^{220}Rn progeny Working Level, WL(Tn), and ^{222}Rn progeny Working Level, WL(Rn), has been determined at Denison Mines Ltd. Experimental measurements extended over a period of one year (1989/90), and consisted of several hundred measurements of each WL(Tn) and WL(Rn). The data were analyzed by standard linear and power-function regression analysis. The relationships obtained permit the calculation of WL(Tn) from experimental values of WL(Rn). The relationship could be useful for radiation exposure calculation purposes and in mine-ventilation-engineering calculations when great accuracy is not mandatory.

Key words: Radon progeny; Thoron progeny; Underground uranium mines.

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RELATIONS ENTRE LES PRODUITS DE FILIATION DU THORON ET LES PRODUITS DE FILIATION DU RADON À LA DENISON MINES LIMITED

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RÉSUMÉ

On trouve des produits de filiation du radon 222 et du radon 220 dans certaines mines d'uranium (U) souterraines canadiennes. Comme les deux types de produits contribuent à l'exposition totale des travailleurs aux rayonnements, la détermination expérimentale de leur concentration est importante. On a déterminé la relation entre l'unité alpha des produits de filiation du ^{220}Rn, WL(Tn), et l'unité alpha des produits de filiation du ^{222}Rn, WL(Rn), à la Denison Mines Ltd. Les mesures expérimentales ont été effectuées sur une période d'un an (1989/90) et comprenaient plusieurs centaines d'évaluations de chacune des grandeurs WL(Tn) et WL(Rn). Les données ont été analysées à l'aide de l'analyse par régression linéaire normale et à fonction puissance. Les relations obtenues permettent de calculer WL(Tn) à partir des valeurs expérimentales de WL(Rn). La relation pourrait être utile à des fins de calcul de la radioexposition et de calcul dans l'étude de la ventilation des mines lorsqu'une grande précision n'est pas requise.

Mots-clés : produits de filiation du radon; produits de filiation du thoron; mines d'uranium souterraines.

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INTRODUCTION

Radon-222 gas and its short-lived progeny are found in relatively high concentrations in operating underground U mines throughout the world. Radon-220 gas and its short-lived decay products, a less common occurrence than ^{222}Rn gas and its progeny, also are found in some underground U mines in Canada and other countries.

It is a commonly accepted practice in Canada, as well as in other nations, to estimate ^{222}Rn progeny concentration alone for dose-calculation purposes. However, because ^{220}Rn progeny, as well as ^{222}Rn progeny, are found in many U mines, it is important to estimate both concentrations for the purpose of controlling and estimating exposures and doses.

The accurate measurement of ^{220}Rn progeny, as well as ^{222}Rn progeny levels in $^{222}Rn/^{220}Rn$ mine atmospheres is not straightforward. It is a lengthy and time-consuming task that severely limits the number of samples that can be used for personal dosimetry and ventilation-engineering purposes. Because of these limitations, it is important to determine whether there is a relationship between ^{222}Rn progeny and ^{220}Rn progeny that can be used to derive one variable from the other with reasonable accuracy.

Because of the short half-life of the ^{222}Rn progeny compared with the relatively long half-life of the ^{220}Rn progeny, the ^{222}Rn progeny are estimated first. Hence, the question is whether ^{222}Rn progeny measurements allow a reliable estimation of ^{220}Rn progeny under average operating field conditions.

This report presents data on the relationship between ^{222}Rn progeny and ^{220}Rn progeny taken over an extended period at Denison Mines Ltd. The data presented here are a follow-up of a similar study conducted over several years at several underground U mines in the Elliot Lake area (1).

THEORETICAL BACKGROUND

Measurements of ^{222}Rn progeny and ^{220}Rn progeny in $^{222}Rn/^{220}Rn$ underground-U-mines atmospheres vary widely in complexity according to the accuracy required and the radiation quantities of interest. A precise, simultaneous, activity concentration measurement of the short-lived decay products of ^{222}Rn (^{218}Po, ^{214}Pb and ^{214}Po) and the short-lived decay products of ^{220}Rn (^{212}Pb and ^{212}Bi) can be carried out using five gross α-counts of a single filter sample (2). This technique also enables the estimation of another useful variable: the Working Level (WL), a variable related to the potential α-energy concentration (PAEC) in air. The PAEC is the potential α-energy concentration corresponding to any mixture of the short-lived decay products of ^{222}Rn or ^{220}Rn present per unit volume of air. The special unit WL corresponds to the ultimate release of α-energy of 1.3×10^5 MeV L^{-1}. The relationship between the WL unit and the PAEC in SI units is: 1 WL = 20.8 μJ m^{-3} (3).

If the progeny concentrations are not necessary and only the Working Level is the variable of interest, simplified counting procedures can be used. Routine measurement of ^{222}Rn progeny Working Level, WL(Rn), and ^{220}Rn progeny Working Level WL(Tn), can be conducted using two gross α-count methods. The methods essentially consist of the following steps:

a) a sampling period, where for moderate activity concentrations, the sampling period is in the range 3-10 min;
b) a waiting period of 40-90 min after the end of sampling followed by an α-counting period of 1-10 min; and
c) a waiting period of 5-11 h after the end of sampling followed by an α-counting period of 5-10 min.

The sampling and α-counting periods suggested above depend mainly on the ^{222}Rn progeny and ^{220}Rn progeny concentrations. For low and very low concentrations, the sampling and counting periods could be substantially

longer than those indicated above.

Steps (a) and (b) describe the Kusnetz method (4) for determining WL(Rn). Steps (a) and (c) correspond to the Rock method (5) for estimating WL(Tn). A more general and detailed method that can be used for both WL(Rn) and WL(Tn) has been developed by this author (6).

The time delay between steps (b) and (c) is necessary to allow essentially complete decay of the ^{222}Rn progeny before counting the ^{220}Rn progeny. However, because of the relatively long half-life of the ^{220}Rn progeny, the α-count obtained in (b) requires correction to take into account the presence of ^{220}Rn progeny.

Knowledge of WL(Tn) and WL(Rn) is not only of interest for the estimation of radiation exposure and dose, but the ratio WL(Tn)/WL(Rn) represents a good indicator of airflow conditions, i.e., ventilation characteristics, in underground U mines (7).

The values of WL(Tn) and WL(Rn), and hence their ratio, in partially enclosed radioactive environments such as those corresponding to underground U mines depend on various factors including:

a) the mass ratio ^{238}U and ^{232}Th;

b) airflow conditions at the location;

c) physical characteristics of the U and Th bearing ore;

d) environmental factors, such as barometric pressure;

e) other factors, such as plate-out of progeny on mine walls and other surfaces; and

f) mining operations.

Items (a), (b), (c) and (f) depend on the location in the mine. Consequently, the ratio WL(Tn)/WL(Rn) should be expected to vary from one mine location to another. In general, however, reasonably representative average values for the mass ratio of $^{238}U/^{232}Th$ and the physical characteristics of the ore can be assumed. Furthermore, if the ventilation characteristics of

the mine are not drastically changed over time, one might anticipate the ratio WL(Tn)/WL(Rn) either to remain approximately constant or to vary within the limits of experimental error in some predictable fashion, at least within the acceptable error for the estimation and control of radiation exposures.

Because different underground U mines may have significantly different ore grades, and hence different mass ratios of $^{238}U/^{232}Th$ and ventilation characteristics, the relationship between WL(Rn) and WL(Tn) could vary substantially from mine to mine. For example, measurements in Ontario U mines show a ratio of WL(Tn)/WL(Rn) of about 0.5 to 0.8, and sometimes higher, whereas mines in Saskatchewan indicate WL(Tn)/WL(Rn) to be approximately 0. Hence, the conclusions derived from experimental data from one mine would not be readily applicable to other mines.

A theoretical derivation of the relationship between WL(Rn) and WL(Tn) under field conditions is beyond the scope of this report. The complexity of diffusion and transport mechanisms of radioactive gases through inhomogeneous and anisotropic media under varying airflow and barometric pressure conditions precludes the treatment of the problem here. Hence, only a useful empirical relationship is sought. However, for a relationship between two variables to be of practical interest and use, the relationship preferably should be a simple one. Two kinds of relationships have been investigated here, a power function and a linear function.

The linear function can be represented as follows:

$$WL(Tn) = mWL(Rn) + b \qquad \text{Eq 1}$$

The power function is represented by Equation 2:

$$WL(Tn) = k[WL(Rn)]^{\alpha} \qquad \text{Eq 2}$$

The power function of Equation 2 can be transformed as follows:

$$\log WL(Tn) = \alpha \log WL(Rn) + \log k, \qquad \text{Eq 3}$$

which is a linear function that should plot as a straight line for log WL(Tn) versus log WL(Rn).

In this report, experimental data on WL(Rn) and WL(Tn) have been collected and analyzed by regression analysis techniques to determine the best data fit according to Equations 1 and 2. Furthermore, a comparison has been made between the two relationships to ascertain the best theoretical fit to the experimental data.

The reader will notice that in the majority of the cases presented here PAEC (Potential Alpha Energy Concentration) data are given in addition to the corresponding WL (Working Level) data. This has been done to conform with modern tendencies to phase out 'units' or definitions no longer widely accepted, and/or used only for historical reasons, in favour of the more logical and rational units according to the SI (Standard International) units system. Hence, in terms of PAEC, Equations 1 and 2 become, respectively.

$$PAEC(Tn) = m\ PAEC(Rn) + b' \text{ , and} \qquad \text{Eq 4}$$

$$PAEC(Tn) = k'[PAEC(Rn)]^{\alpha} \qquad \text{Eq 5}$$

where, $b' = \epsilon b$, and Eq 6

$$k' = \epsilon^{(1-\alpha)}\ k \qquad \text{Eq 7}$$

and where, ϵ = PAEC/WL = 20.8 $\mu J\ m^{-3}$.

EXPERIMENTAL PROCEDURE

The ^{222}Rn and ^{220}Rn progeny WL data presented in this paper were obtained at several locations within the same mine. The U and Th mass concentrations in the geological formation, where the U mines investigated were located, were as follows: 0.05% for Th in the form of ThO_2; from less than 0.05% to about 0.35%, with an average value of 0.1%, for U in the form of U_3O_8. Hence, the average mass ratio of $^{238}U/^{232}Th$ is approximately two.

Measurements were made by the mine personnel over the period 1989 to 1990. The discussion presented in this report is based on several hundred independent measurements (samples) of both WL(Rn) and WL(Tn). After determination of WL(Rn) and WL(Tn), and of their corresponding PAEC's, i.e.,

PAEC(Rn) and PAEC(Tn), respectively, frequency histograms were plotted, and the correlations between WL(Tn) and WL(Rn), and between PAEC(Tn) and PAEC(Rn) were determined by regression analysis using least squares techniques, and Equations 1 to 3 as shown in the next section.

EXPERIMENTAL RESULTS AND DISCUSSION

The experimental data have been summarized in Figures 1 to 11. Figures 1 to 4 show frequency histograms of WL(Rn), WL(Tn), PAEC(Rn) and PAEC(Tn). Figures 5 and 6 show frequency histograms corresponding to PAEC(Rn) - $\overline{\text{PAEC(Rn)}}$, and PAEC(Tn) - $\overline{\text{PAEC(Tn)}}$, respectively, where the horizontal bars are used to indicate average or mean value of all the PAEC(Rn), or PAEC(Tn) measurements. Figures 7 to 11 show the relationship (experimental data) between WL(Tn) and WL(Rn) and between PAEC(Tn) and PAEC(Rn). Also shown in these graphs are the best fitted lines by regression analysis using least squares techniques.

Figures 1 and 2 show relatively narrow frequency distributions for WL(Rn) and PAEC(Rn), respectively. The histograms indicate that over 80% of the values for WL(Rn) and PAEC(Rn) are equal to, or less than, 0.31 and 6 $\mu J\ m^{-3}$, respectively. About 43% of the values for WL(Rn) and PAEC(Rn) are below, or equal to, 0.1 and 2 μJm^{-3}, respectively.

Figures 3 and 4 show somewhat broader frequency distributions for WL(Tn) and PAEC(Tn) than their respective counterparts for ^{222}Rn progeny. the wider spread shown in these histograms is most certainly related to the experimental procedures followed by mine personnel and the statistics of counting, as discussed below. The percentage of values below WL(Tn) = 0.3 (PAEC(Tn) ~6 μJm^{-3}) and below WL(Tn) = 0.1 (PAEC(Tn) ~2 μJm^{-3}), are however, only slightly less than those of Figures 1 and 2, namely 80% and 35%, respectively. A large fraction of the total number of determinations was below WL(Tn) ~0.2, with a maximum between 0.05 and 0.10.

The data of Figures 5 and 6 clearly show a significant bias for the values of PAEC(Rn) and PAEC(Tn) below their respective arithmetic means. The reason for the skewness observed is not yet clear.

Figures 7 to 11 show the experimental data obtained as well as the best fitted lines by least squares regression analysis. The best fitted straight lines to the PAEC(Rn) and PAEC(Tn) data points are shown in Figure 7, whereas Figure 8 shows the best fitted power function to the same data. In Figures 10 and 11 the best fitted linear and power functions to the data are shown together, for comparison purposes, for the WLs and PAECs, respectively. Figure 9 shows a best polynomial fit, for illustration purposes. The analytical equations corresponding to the above graphs are given below:

$$WL(Tn) = 0.339\ WL(Rn) + 0.133 \quad ; \quad R^2 = 0.474 \quad ; \quad R = 0.69 \qquad \text{Eq 8}$$

$$WL(Tn) = 0.526\ WL(Rn)^{0.6306} \quad ; \quad R^2 = 0.527 \quad ; \quad R = 0.73 \qquad \text{Eq 9}$$

$$PAEC(Tn) = 0.339\ PAEC(Rn) + 2.763 \quad ; \quad R^2 = 0.474 \quad ; \quad R = 0.69 \qquad \text{Eq 10}$$

$$PAEC(Tn) = 1.613\ [PAEC(Rn)]^{0.6306} \quad ; \quad R^2 = 0.527 \quad ; \quad R = 0.73 \qquad \text{Eq 11}$$

$$PAEC(Tn) = 1.189 + 0.877\ PAEC(Rn) - 0.01338\ [PAEC(Rn)]^2 \qquad \text{Eq 12}$$

In the above expressions, R is the correlation coefficient. Because values for PAEC(Rn) and PAEC(Tn) greater than 20 μJm^{-3} (i.e., WL ~1) were rarely found, linear and power regression analyses on the data were conducted within the limits $0 \leq PAEC \lesssim 20\ \mu Jm^{-3}$. The results are shown below:

$$PAEC(Tn) = 0.735\ PAEC(Rn) + 1.4 \quad ; \quad R^2 = 0.537 \quad ; \quad R = 0.73 \qquad \text{Eq 13}$$

$$PAEC(Tn) = 1.582\ [PAEC(Rn)]^{0.677} \quad ; \quad R^2 = 0.521 \quad ; \quad R = 0.72 \qquad \text{Eq 14}$$

The above expressions have been summarized in tabular form (see Table 1) according to the nomenclature indicated in Equations 1, 2, 4 and 5. Also shown in this table (for comparison purposes) are correlation parameters obtained in two previous, long-term, studies published elsewhere (1,8). The different values for the correlation coefficients obtained in the present study and in these former studies will be discussed below. However, the most significant difference between these different sets of data is the higher

correlation obtained in previous work.

Tables 2 and 3 show data predicted by Equations 8 and 9 (Table 2), and Equations 10 and 11 (Table 3). Also shown in Table 2 in round brackets are the values corresponding to previous studies (1,8) for reference purposes. Both tables also include the ratio of the progeny values of interest calculated according to the linear function correlation and the power function correlation.

The linear functions show WL(Tn) >0 and PAEC(Tn) >0 when WL(Rn) = 0, and PAEC(Rn) = 0, respectively. This situation corresponds to a very large value of the ratios WL(Tn)/WL(Rn) and PAEC(Tn)/PAEC(Rn), which can occur only under either extremely high ventilation conditions, i.e., very 'young' mine air, or for a very low mass ratio of $^{238}U/^{232}Th$, or both. This is a rather unlikely situation and this result is most likely due to a mathematical (statistical) artifact. The power function predicts PAEC(Tn) = 0 for PAEC(Rn) = 0, naturally, WL(Tn) = 0 for WL(Rn) = 0, a result to be expected from the form of the power expression used.

Tables 2 and 3 show substantial disagreement between the values predicted by the linear and power correlations for WL(Tn) when WL(Rn) $\lesssim$0.12, and for PAEC(Tn) when PAEC(Rn) $\lesssim$2 μJm^{-3}. In both cases there is a discrepancy of $\gtrsim$20%. Agreement between the predictions by these two functions (linear and power) improves as WL(Rn) or PAEC(Rn) increase, up to a certain value, and then the agreement worsens slightly (~10-13%).

Table 2 also shows the ratio $WL(Tn)_{max}$ to $WL(Tn)_{min}$ taken from the three sets of values given for each value of WL(Rn). These data show that on average the power functions for the three sets of data seem to agree somewhat better than the corresponding linear functions. However, despite this result, it is not readily obvious which function, i.e., linear or power, better describes and fits the experimental data because their respective correlation coefficients do not differ markedly. In the region of most interest, namely,

$0.05 \lesssim WL(Rn) \lesssim 0.3$, a disagreement (as measured by the ratio $WL(Tn)_{PF}/WL(Tn)_{LF}$) of close to 100%, for the lowest WL(Rn) value, should be expected. Finally, a comparison of the theoretical values predicted for WL(Tn), for each value of WL(Rn), according to linear function (LF) and power function (PF) correlation data for the three sets of experimental data available (i.e., this work and the data corresponding to references 1 and 8) show a disagreement between sets of data of up to 50%.

Rather than ponder the reasons for the above disagreements, it is best to analyze the theoretical roots of these disagreements. There are two main reasons to be considered:

1. The ratio WL(Tn)/WL(Rn) can be predicted on theoretical grounds. This ratio is shown to depend on airflow conditions (Q), and the mass ratio $^{238}U/^{232}Th$.
2. Item 1 depends on the theoretical mine model chosen to describe the growth and decay of ^{222}Rn and ^{220}Rn progeny radioactivity in mine air, which in turn depends on the basic assumptions made in the model.

Items 1 and 2 have been analyzed in detail elsewhere (7), and further theoretical discussion on this topic is beyond the scope of this report. The important point here is that the relationship between WL(Tn) and WL(Rn) calculated from experimental data for a given mine location will rarely be the same if Q does not remain constant. Likewise, the above relationship will vary for mine locations where Q, and/or the mass ratio $^{238}U/^{232}Th$ are different. Hence, criteria and 'tolerance' limits have to be established within which a relationship between WL(Tn) and WL(Rn) can be considered reasonably accurate and broad enough that can be used meaningfully for its intended purpose.

In addition to items 1 and 2 above, other factors affect the accuracy of the relationship between WL(Tn) and WL(Rn), such as:

a) Experimental procedures and measurement techniques and methods used; and

b) Statistics of counting. This item is partly related to item a).

CONCLUSIONS AND RECOMMENDATIONS

The discussion presented in this report can be summarized as follows:

i) The empirical expressions derived in this work are not substantially or fundamentally different from other expressions obtained previously from other experimental studies of the same nature.

ii) From the empirical standpoint there is no overwhelming evidence to favour the linear function expression over the power function expression, or vice versa.

iii) Each independent new set of measurements underground will give different relationships between WL(Tn) and WL(Rn) because of items 1 and 2, and to a lesser extent to items a) and b).

Because of items i) to iii), a decision must be made regarding the accuracy required for whatever analytical expression relating WL(Tn) and WL(Rn), or PAEC(Tn) and PAEC(Rn), is to be used. This should depend on the intended purpose of this expression, and 'tolerance limits' should, therefore, be set for the main parameters describing the analytical expression derived from experimental data using least squares correlation techniques or other techniques.

It should be emphasized that more experimental, parallel measurements of WL(Tn) and WL(Rn) alone will not improve our knowledge of the relationship between these two variables. In order to gain insight into this problem, concurrent measurements should also be conducted of airflow conditions, and detailed knowledge of the mass ratio $^{238}U/^{232}Tn$ and mining operations should be available. This, however, would impose a severe burden on the experimenters and it is not altogether clear that the reward obtained would be justified in terms of effort, man-power and resources. In the meantime, it is suggested that adequate experimentation has already been done on the subject,

and now, a decision should be made as to whether or not the data so far obtained, and the analytical expressions derived from those data, are accurate and reliable enough, under a broad range of mine environmental conditions, to justify their use. The alternative to using an analytical expression to derive WL(Tn) from routine measurements of WL(Rn) is clear and straightforward, namely, concurrent or parallel measurement of WL(Tn), on the same filter sample, in addition to the determination of WL(Rn).

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Table 1 - Regression parameters for the linear and power functions investigated here.

Variable Relationship	Linear Parameters m	b	Power Parameters k	α	Modified Parameters b'	k'	R(L)	R(P)	Remarks
WL	0.339	0.133	0.526	0.6306	-	-	0.69	0.73	This work
WL	0.470	0.074	0.557	0.7270	-	-	0.83	0.94	Ref. 1
WL	0.878	0.052	0.610	0.605	-	-	0.93	0.82	Ref. 8
PAEC	0.339	-	-	0.6306	2.763	1.613	0.69	0.73	This work
PAEC	0.735	-	-	0.6770	1.40	1.582	0.73	0.72	This work*

Notes: * for PAEC(Rn) and PAEC(Tn) equal or less than 20 μJm^{-3}.

a) R(L) and R(P) stand for correlation coefficient corresponding to the linear function and power function, respectively.

b) For a definition of the regression parameters m, b, k, α, b' = 20.8 b and $k' = (20.8)^{(1-\alpha)}\ k$ see Equations 1 to 6.

Table 2 - Theoretical data calculated with linear and power functions

WL(Rn)	$WL(Tn)_{LF}$	$WL(Tn)_{PF}$	$\frac{WL(Tn)_{PF}}{WL(Tn)_{LF}}$	$\frac{WL(Tn)_{max}}{WL(Tn)_{min}}$ LF	PF
0	0.133 (0.074 ; 0.052)	0 (0 : 0)	0 (0 ; 0)	2.56	Ind.
0.01	0.136 (0.079 ; 0.061)	0.029 (0.020 ; 0.038)	0.21 (0.25 ; 0.62)	2.23	1.90
0.02	0.140 (0.083 ; 0.070)	0.045 (0.032 : 0.057)	0.32 (0.38 ; 0.81)	2.00	1.78
0.03	0.143 (0.088 ; 0.079)	0.058 (0.043 ; 0.073)	0.41 (0.49 ; 0.92)	1.81	1.70
0.04	0.146 (0.093 ; 0.087)	0.069 (0.054 ; 0.087)	0.47 (0.58 ; 1.00)	1.68	1.61
0.05	0.150 (0.097 ; 0.096)	0.079 (0.063 ; 0.100)	0.53 (0.65 ; 1.04)	1.56	1.59
0.075	0.158 (0.109 ; 0.118)	0.103 (0.085 ; 0.127)	0.65 (0.78 ; 1.08)	1.45	1.49
0.100	0.167 (0.121 ; 0.140)	0.123 (0.104 ; 0.151)	0.74 (0.86 ; 1.08)	1.38	1.45
0.12	0.174 (0.130 ; 0.158)	0.138 (0.119 ; 0.169)	0.79 (0.91 ; 1.07)	1.34	1.42
0.15	0.184 (0.144 ; 0.184)	0.159 (0.140 ; 0.193)	0.86 (0.97 ; 1.05)	1.28	1.38
0.17	0.191 (0.154 ; 0.201)	0.172 (0.154 ; 0.209)	0.90 (1.00 ; 1.04)	1.30	1.36
0.20	0.201 (0.168 ; 0.228)	0.191 (0.173 ; 0.230)	0.95 (1.03 ; 1.01)	1.36	1.33
0.25	0.218 (0.191 ; 0.272)	0.219 (0.203 ; 0.264)	1.00 (1.06 ; 0.97)	1.42	1.30
0.30	0.235 (0.215 ; 0.316)	0.246 (0.232 ; 0.294)	1.05 (1.08 ; 0.93)	1.47	1.27
0.35	0.252 (0.238 ; 0.360)	0.271 (0.260 ; 0.323)	1.07 (1.09 ; 0.90)	1.51	1.24
0.40	0.269 (0.262 ; 0.403)	0.295 (0.286 ; 0.350)	1.10 (1.09 ; 0.87)	1.54	1.22
0.50	0.302 (0.309 ; 0.490)	0.340 (0.336 ; 0.401)	1.13 (1.09 ; 0.82)	1.62	1.19
0.60	0.336 (0.356 ; 0.579)	0.381 (0.384 ; 0.448)	1.13 (1.08 ; 0.77)	1.72	1.18
1.00	0.472 (0.544 ; 0.930)	0.526 (0.557 ; 0.610)	1.11 (1.02 ; 0.66)	1.97	1.16

Notes: a) The subindices LF and PF stand for linear function and power function, respectively.

b) The values in round brackets correspond to an earlier study reported in references 1 and 8, respectively.

Table 3 - Theoretical data calculated with linear and power functions

PAEC(Rn) (μJm^{-3})	$PAEC(Tn)_{LF}$ (μJm^{-3})	$PAEC(Tn)_{PF}$ (μJm^{-3})	$\frac{PAEC(Tn)_{PF}}{PAEC(Tn)_{LF}}$
0	2.763	0	0
1	3.102	1.613	0.52
2	3.441	2.498	0.73
3	3.780	3.225	0.85
4	4.119	3.867	0.94
5	4.458	4.451	~1.00
6	4.797	4.994	1.04
7	5.136	5.503	1.07
8	5.475	5.987	1.09
9	5.814	6.448	1.11
10	6.153	6.891	1.12
11	6.492	7.318	1.13
12	6.831	7.731	1.13
13	7.170	8.131	1.13
14	7.509	8.520	1.13
15	7.848	8.899	1.13
16	8.187	9.269	1.13
17	8.526	9.630	1.13
18	8.865	9.984	1.13
19	9.204	10.330	1.12
20	9.543	10.669	1.12

Note: The subindices LF and PF stand for linear function and power function, respectively.

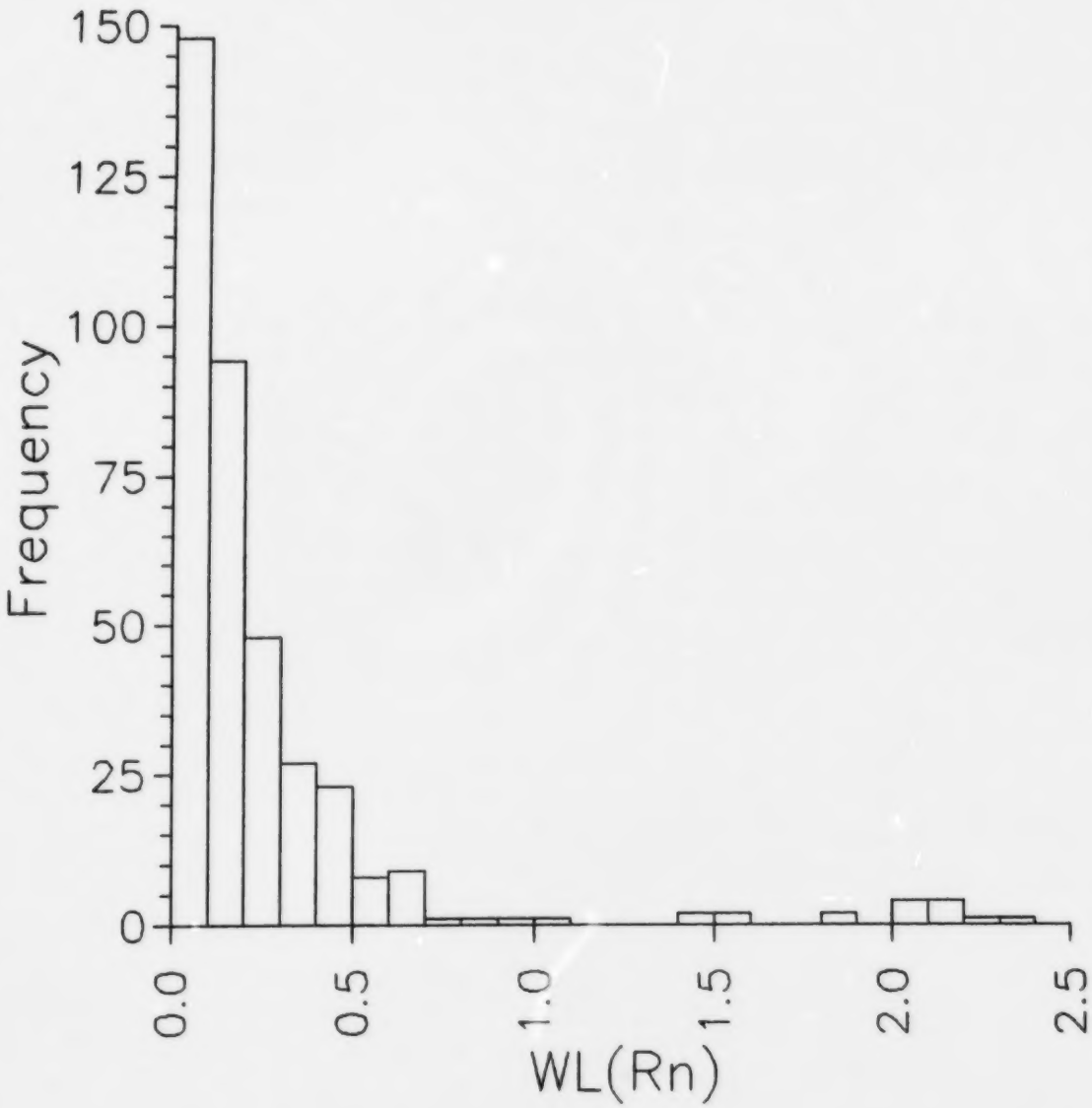

Fig. 1 - ^{222}Rn progeny Working Level frequency histogram.

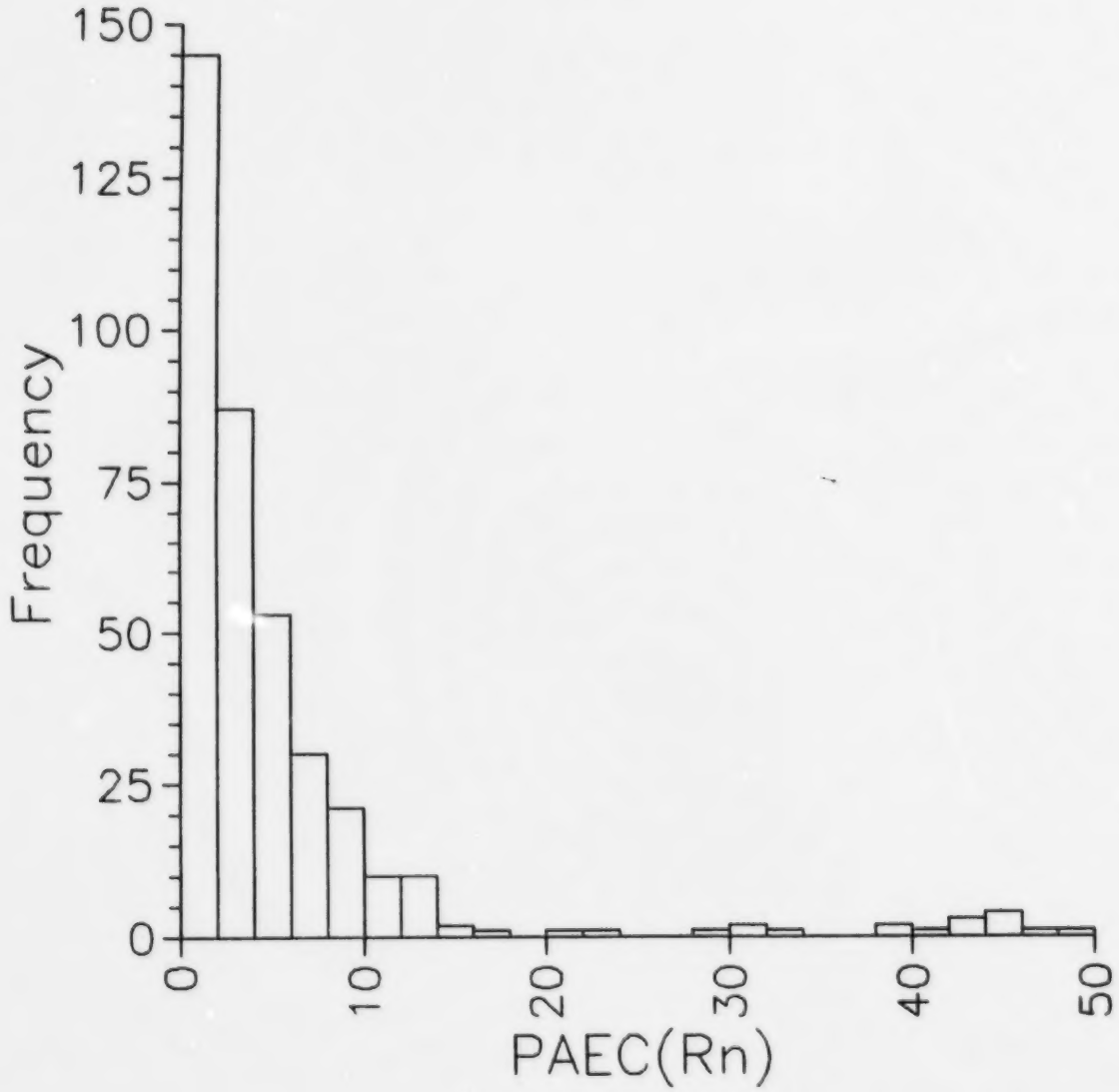

Fig. 2 - ^{222}Rn progeny PAEC frequency histogram.

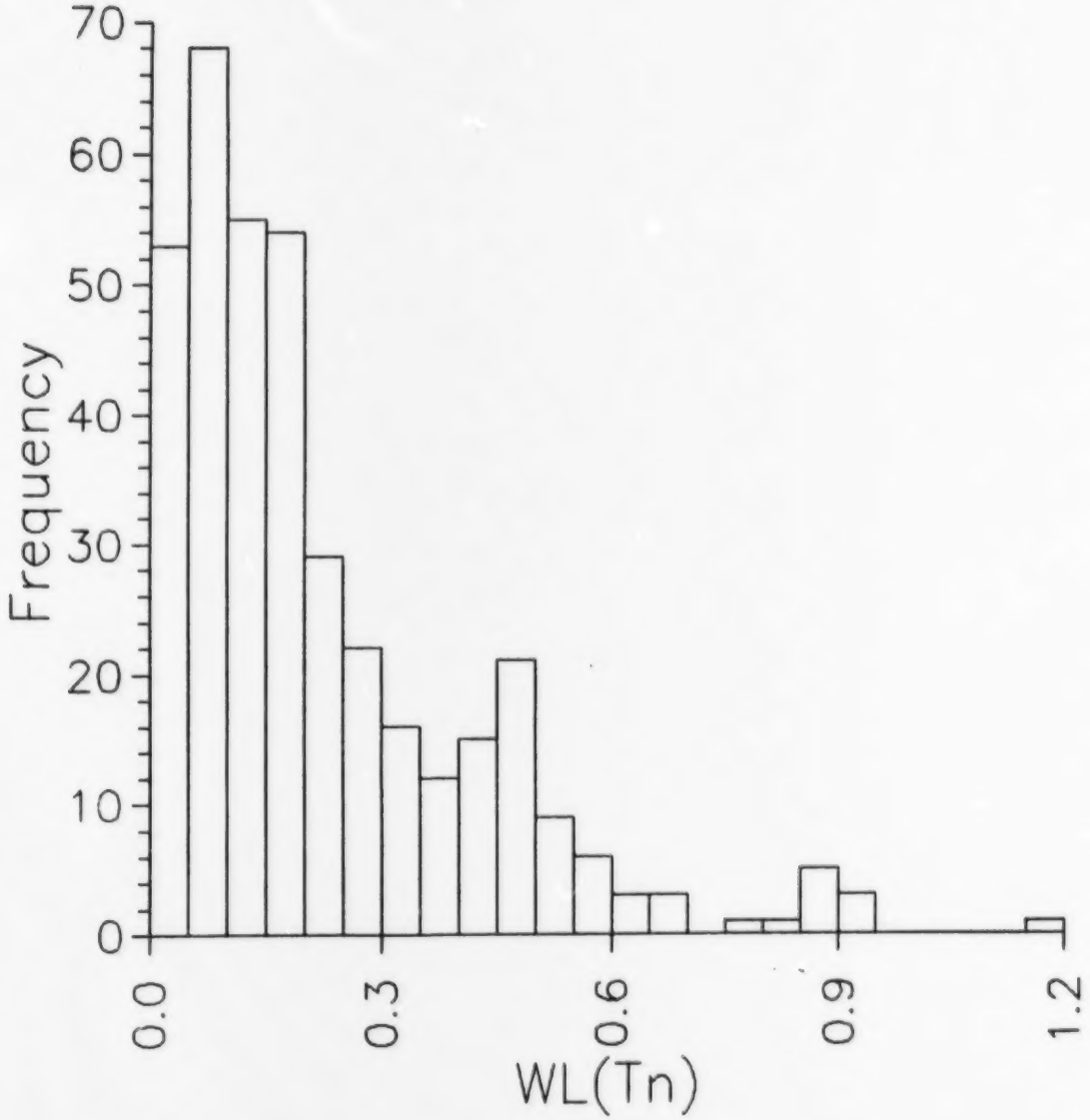

Fig. 3 - ^{220}Rn progeny Working Level frequency histogram.

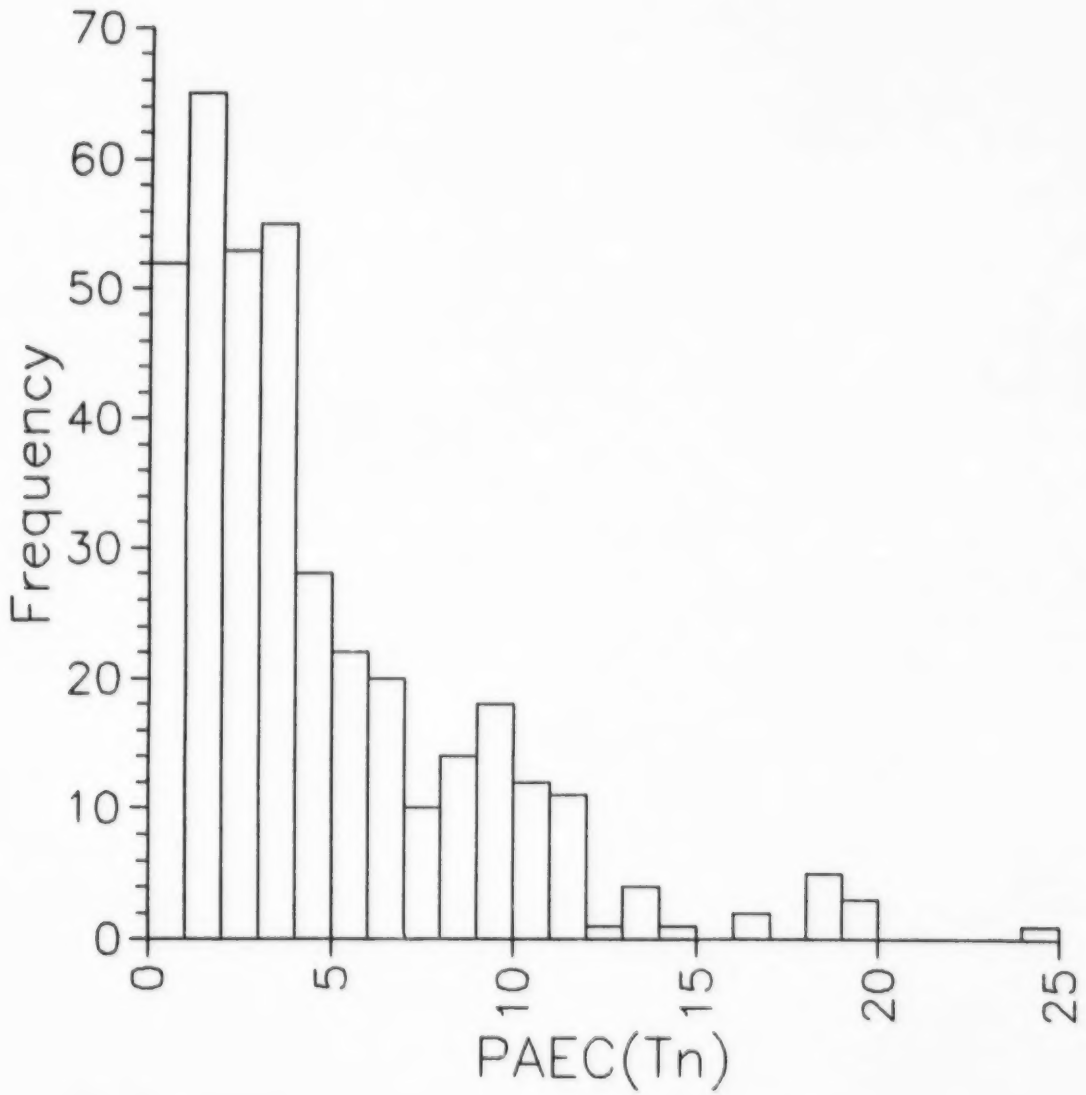

Fig. 4 - ^{220}Rn progeny PAEC frequency histogram.

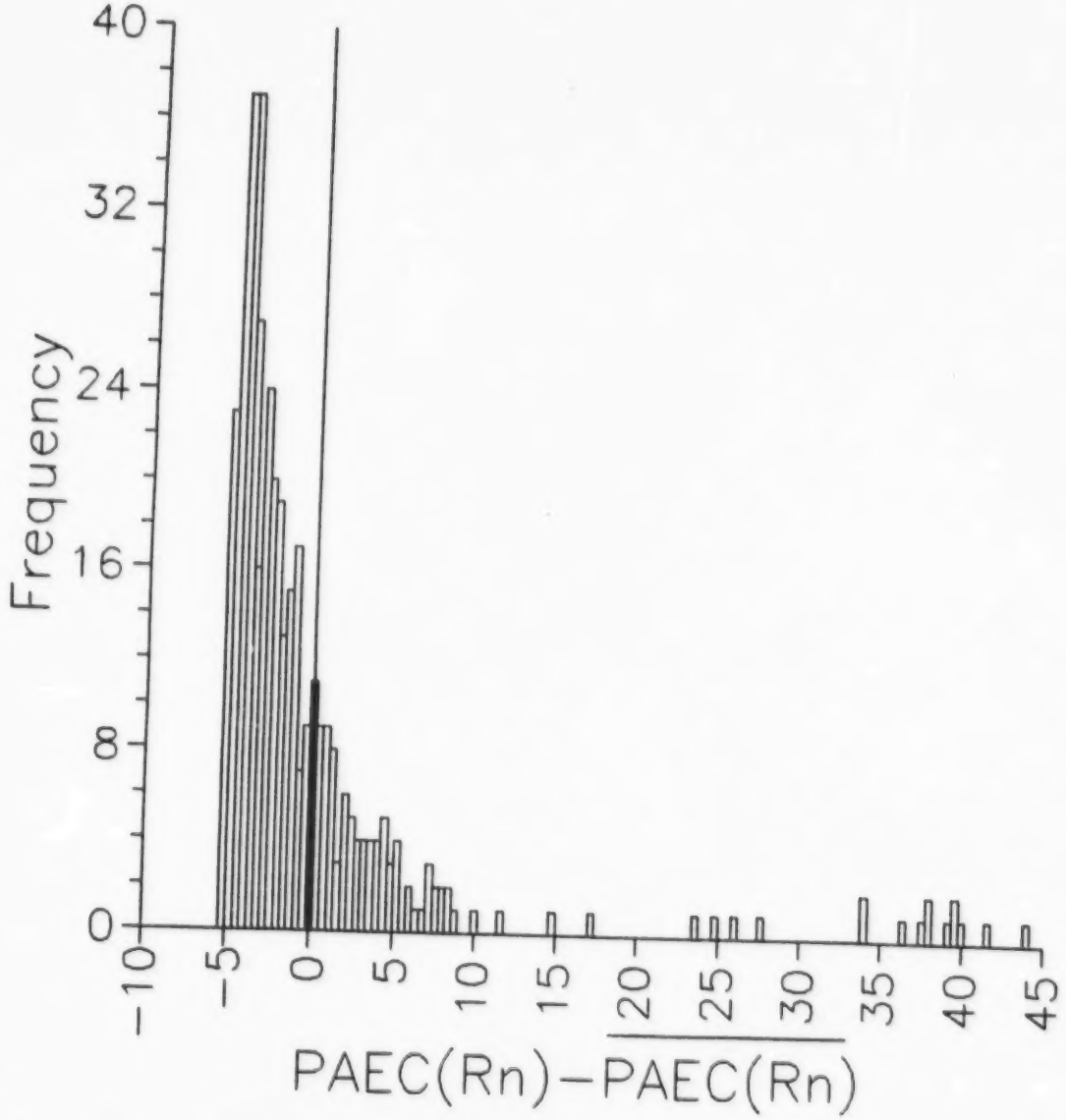

Fig. 5 - PAEC(Rn) - $\overline{\text{PAEC(Rn)}}$ frequency histogram.

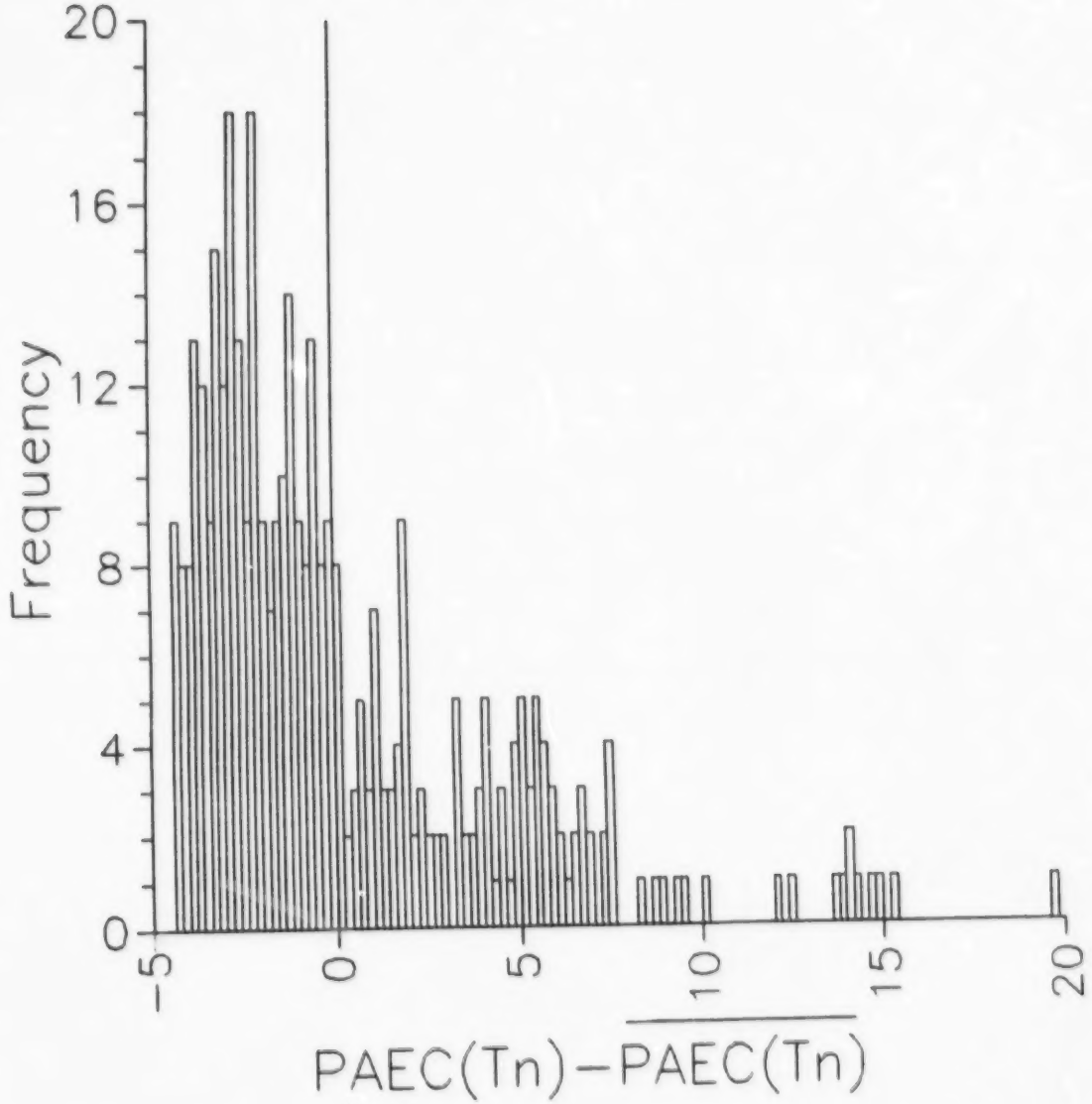

Fig. 6 - PAEC(Tn) - $\overline{\text{PAEC(Tn)}}$ frequency histogram.

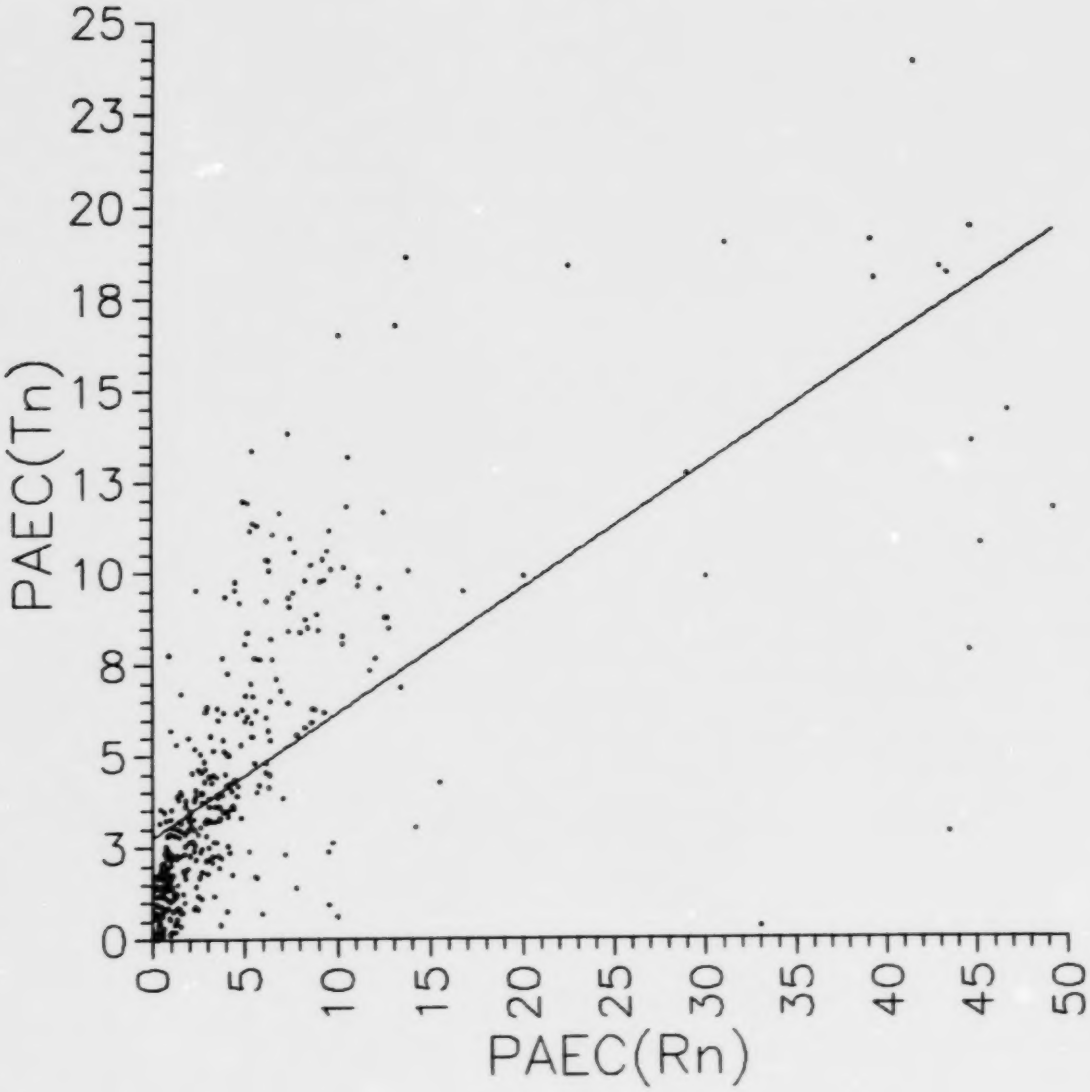

Fig. 7 - PAEC(Tn) versus PAEC(Rn). Also shown is the best fitted straight line to the data points by linear regression analysis.

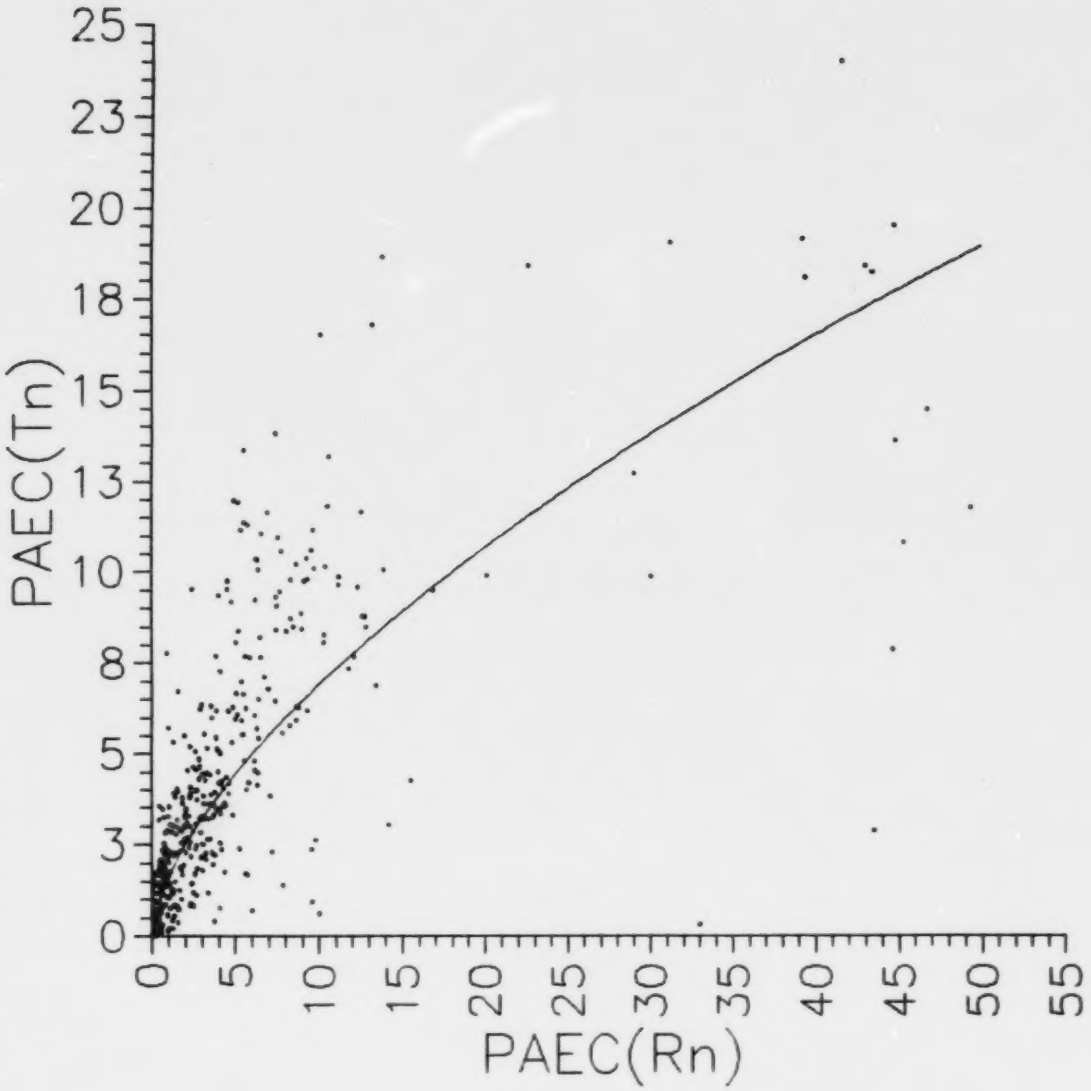

Fig. 8 - PAEC(Tn) versus PAEC(Rn). Also shown is the best fitted power function to the data points by regression analysis.

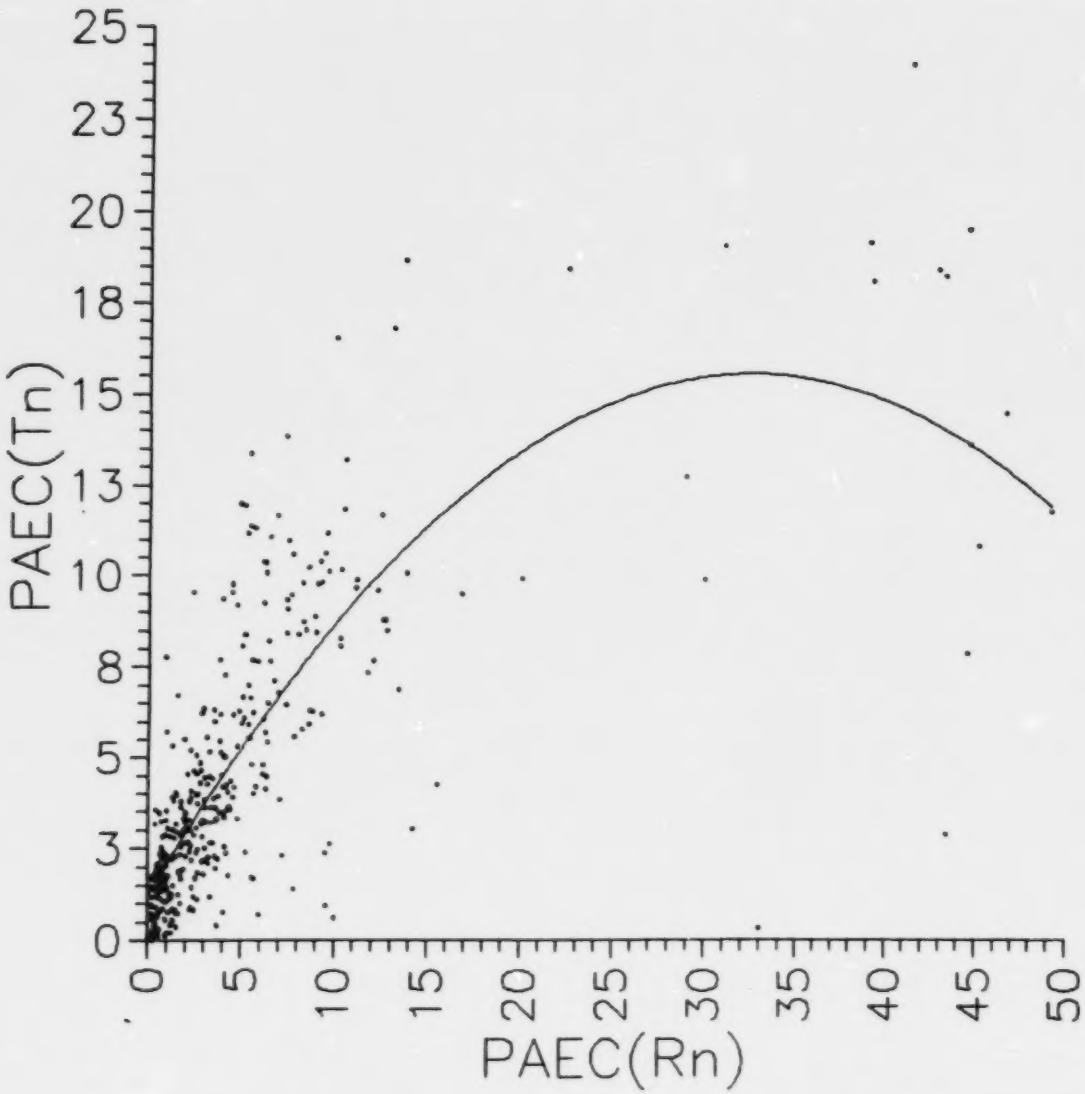

Fig. 9 - PAEC(Tn) versus PAEC(Rn). Also shown is the best fitted polynomial by regression analysis.

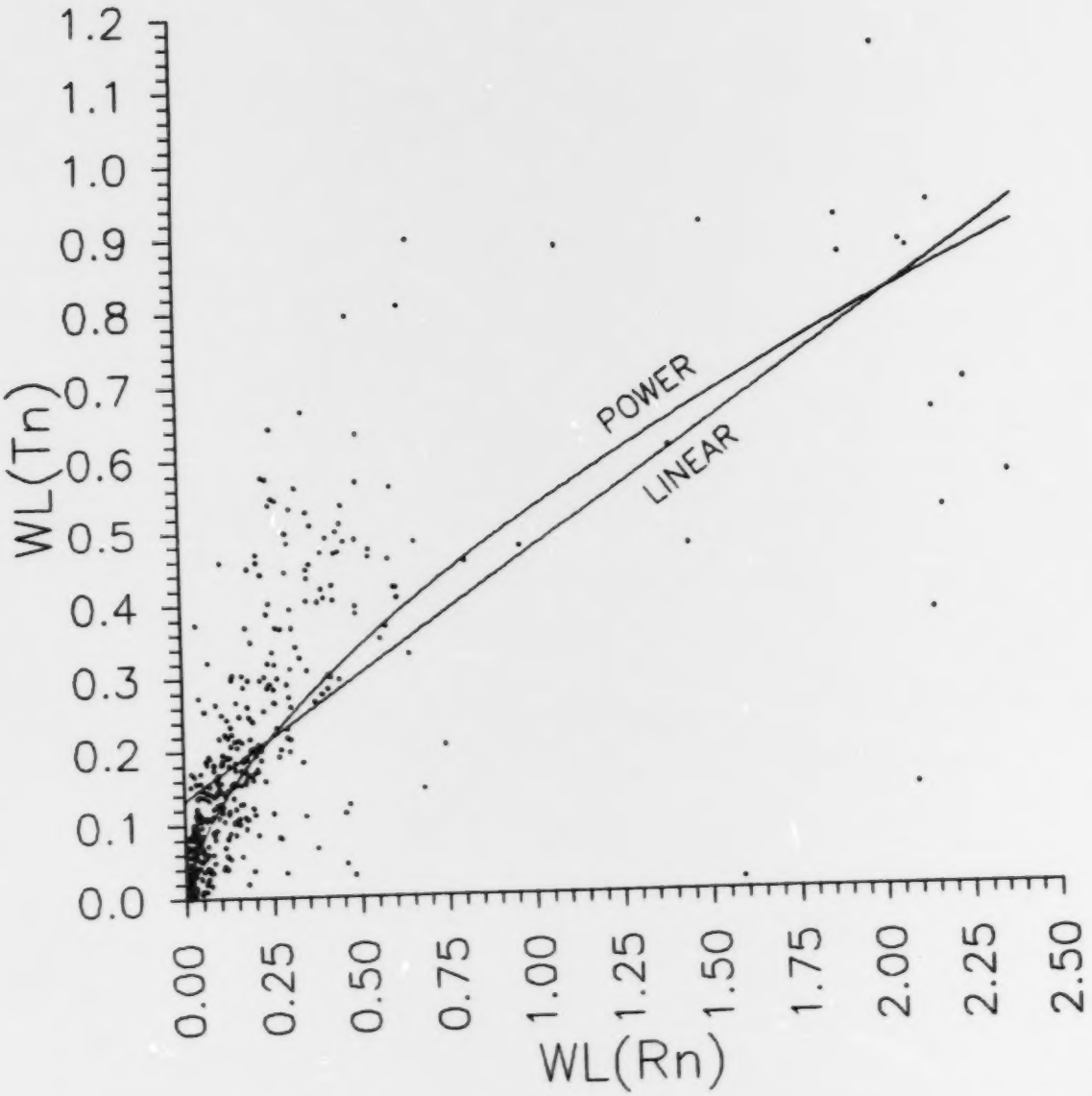

Fig. 10 - WL(Tn) versus WL(Rn). Also shown are the best fitted linear and power functions by regression analysis.

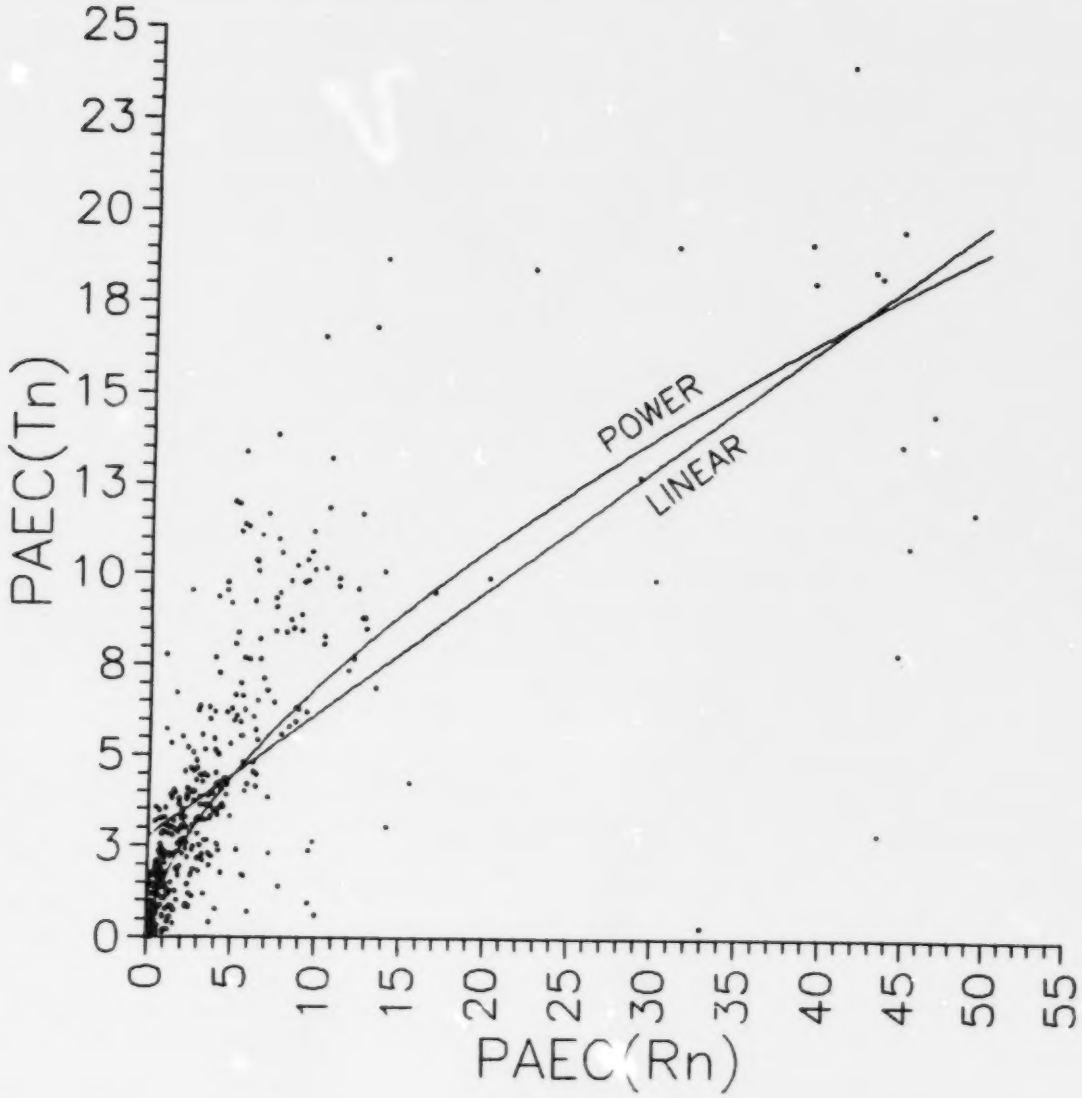

Fig. 11 - PAEC(Tn) versus PAEC(Rn). Also shown are the best fitted linear and power functions by regression analysis.